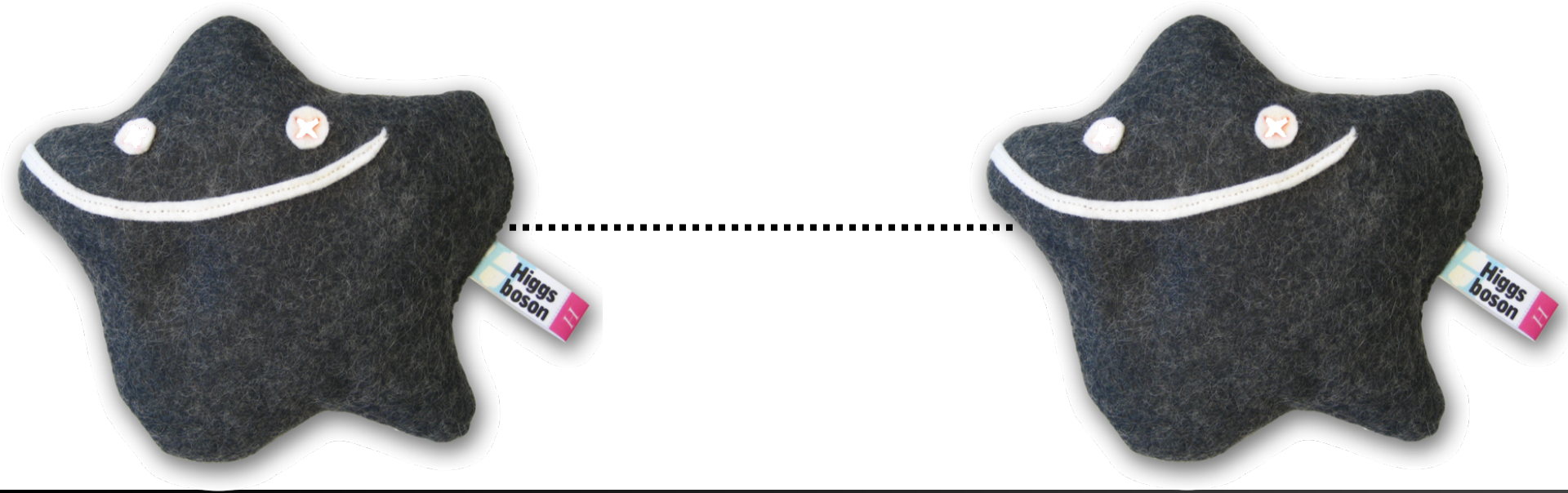
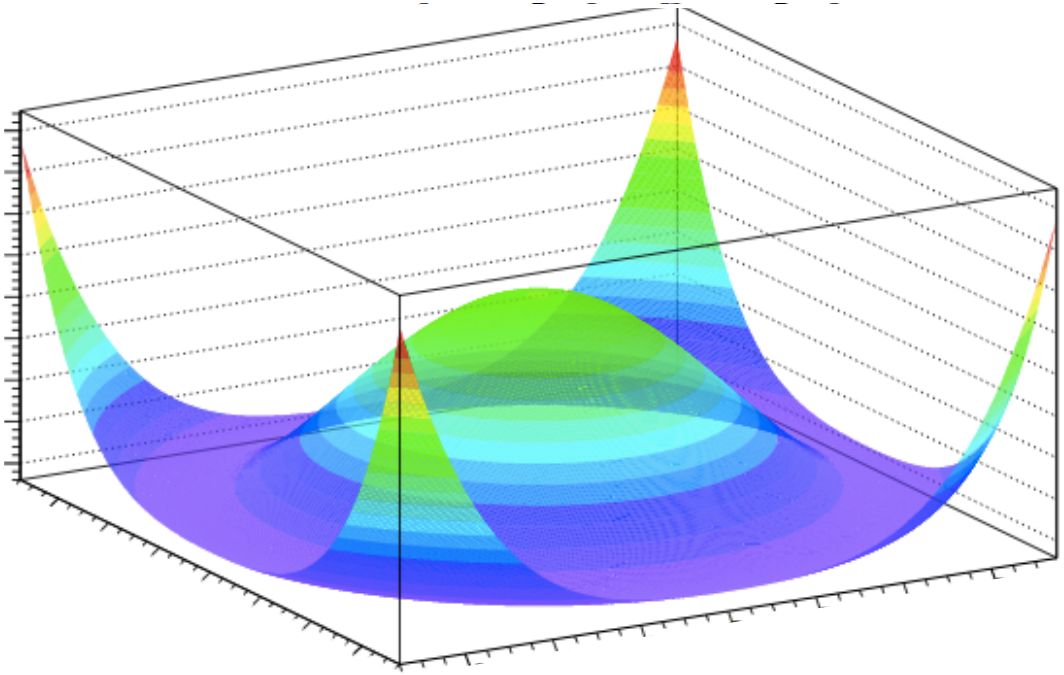
HL-LHC/FCC-hh DiHiggs searches

Jahred Adelman



Key long-term LHC (and beyond!) goal

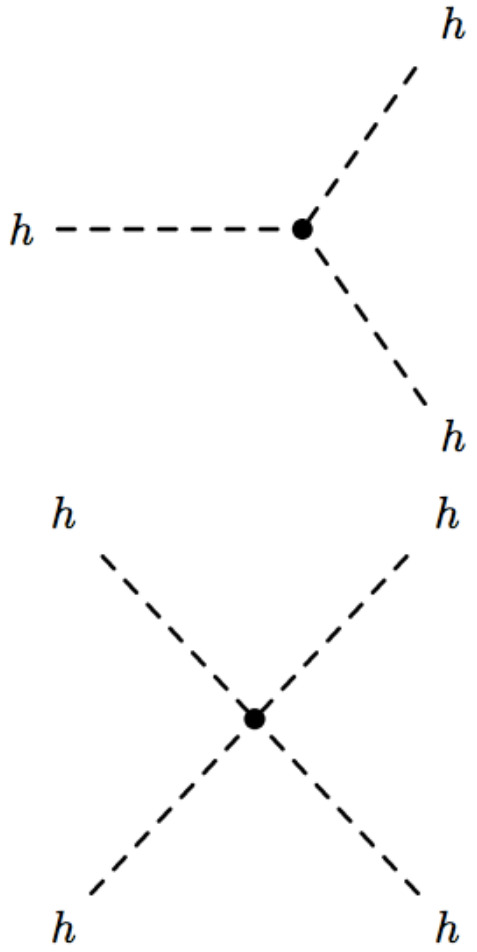
Observe the **Higgs boson self-coupling**, crucial to testing if the Higgs potential is the one predicted in the Standard Model (SM)



$$\mathcal{L}_V = -\lambda v^2 h^2 - \lambda v h^3 - \frac{\lambda}{4} h^4$$

Reminder: Why do we care so much about this?

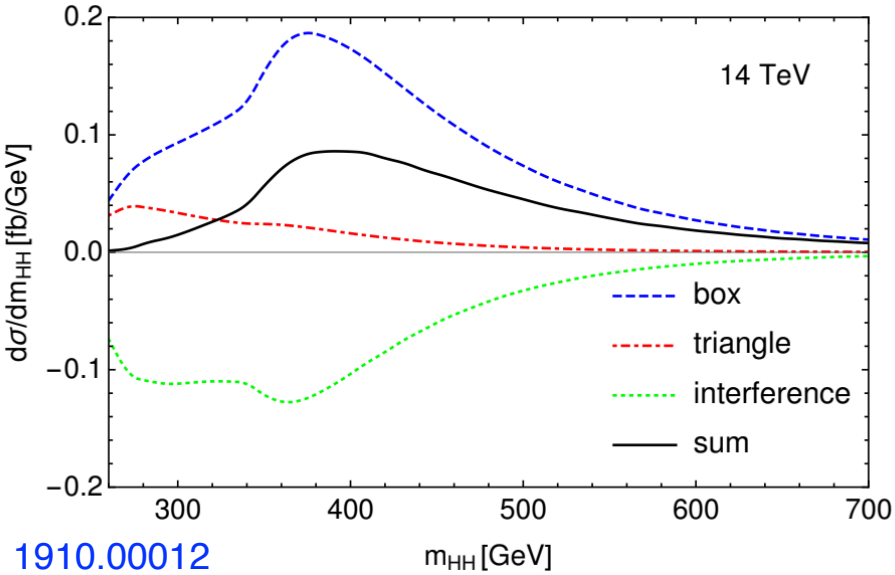
- Study the exact dynamics of **electroweak symmetry breaking**, map out the Higgs boson potential
- Further our understanding of potential solutions to the **hierarchy problem**
- As a window into new **physics beyond the SM**
- Study EWSB to understand **matter-antimatter imbalance** and EW baryogenesis



Where might you study this?

SM hh production dominated by **box diagram**, not hh self-coupling of **triangle diagram**, with **destructive interference** between the two

Reminder: It took 40 years to observe the Higgs boson. We've good great machines and we're clever, but unless BSM physics completely surprises us, we'll need **lots of luminosity and √s** (HL-LHC and FCC-hh are great options)



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Need **differential measurements** to understand κ_λ

LHC: hh production **3 orders of magnitude** more rare than single h production!

ATL-PHYS-PUB-2018-053 and

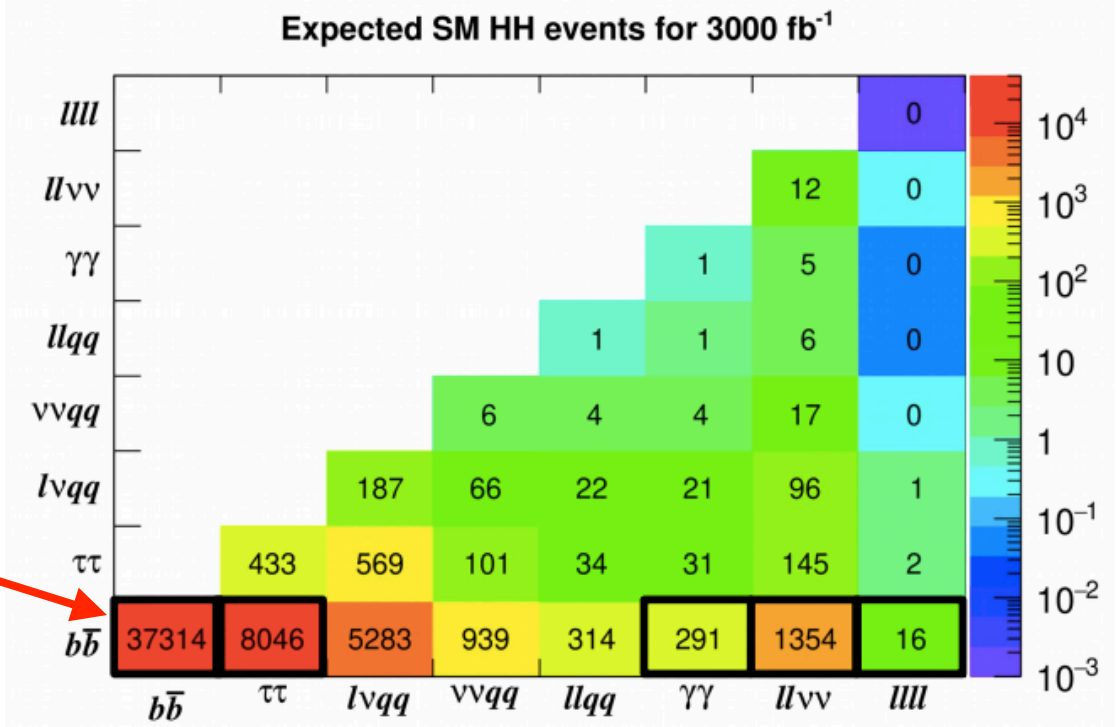
CMS-PAS FTR-18-019

Reminder: **HL-LHC** is needed by the LHC to observe SM hh production (and even then, it **won't be a piece of cake**)

Quick recap of what we know about the HL-LHC searches …

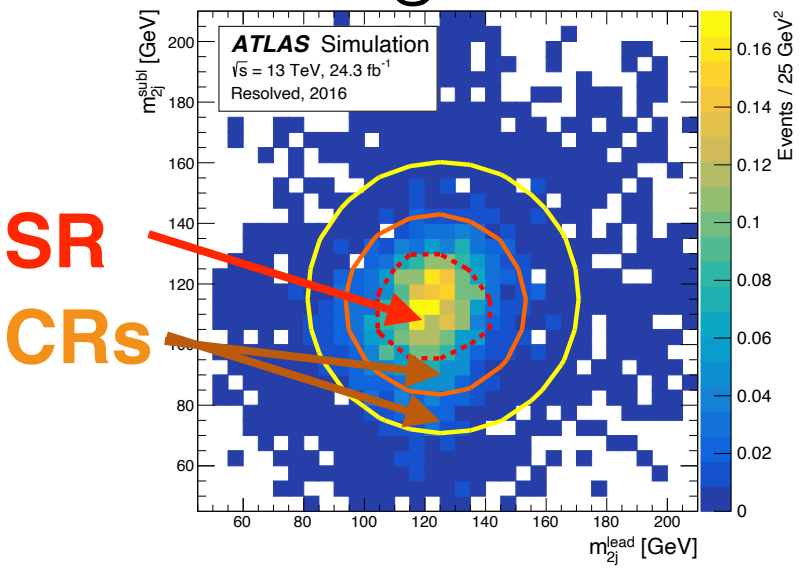
Studying HL-LHC prospects

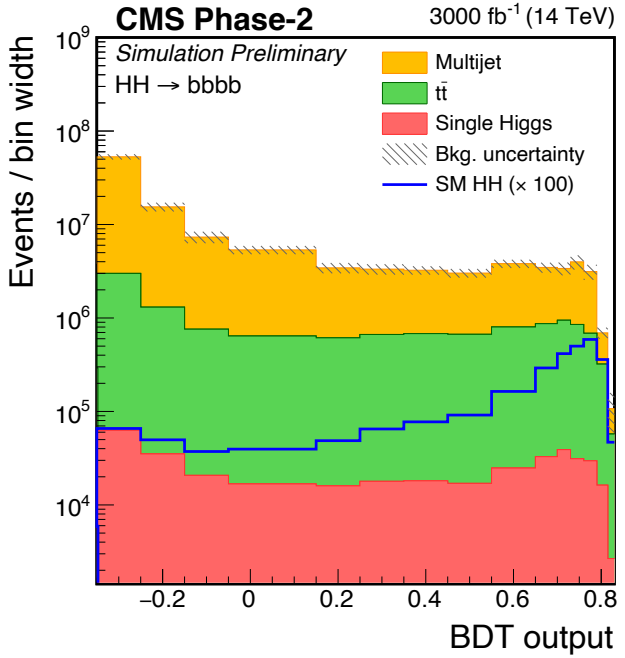
4b channel is an obvious one, with the **highest hh BR**. Challenge: Large backgrounds (multijet and ttbar)



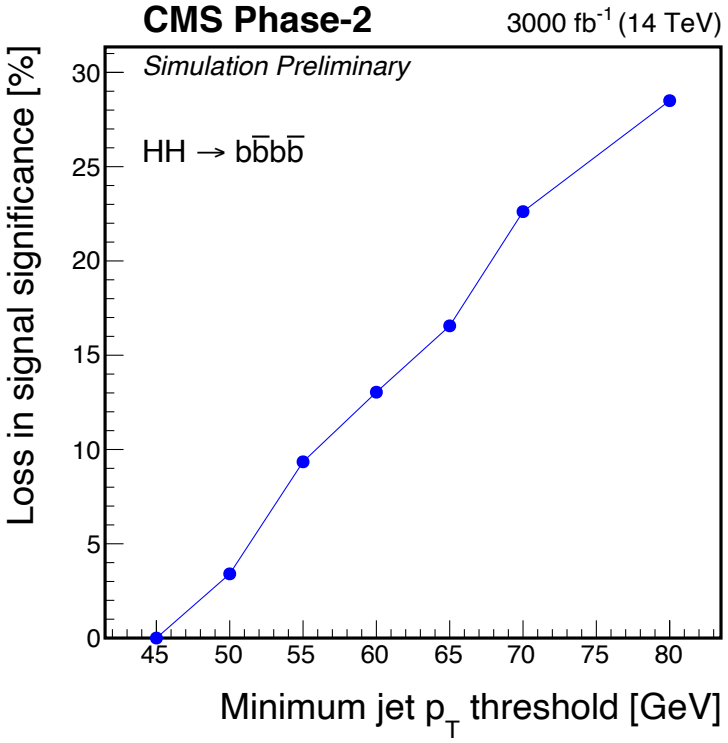
- **Multi-jet and ttbar** background critical to understand
- **Increased b-tagging efficiency** important, boosted topology for BSM
- **Trigger** is tricky and crucial to understand (combination of multijet and b-jet triggers?)
- Roughly **1.0-1.5σ at 3 ab-1**, but systematics degrade performance significantly

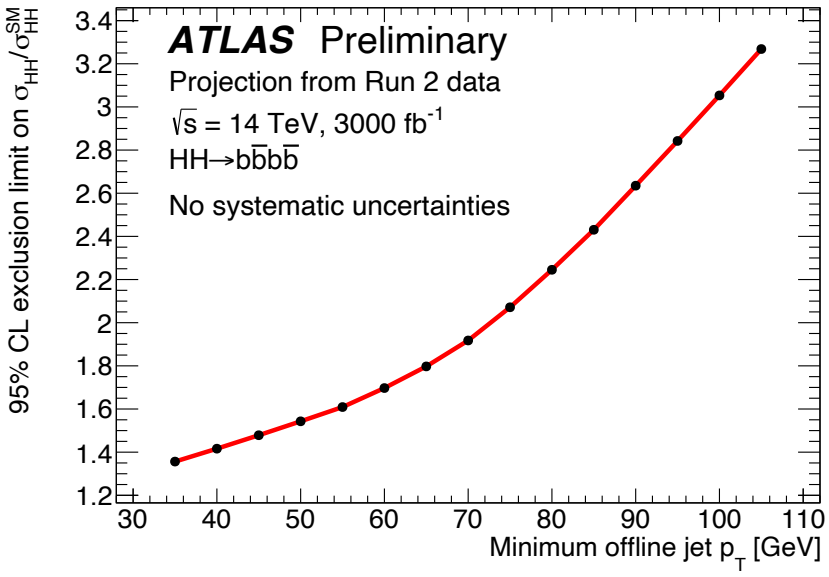
Signal





hh(4b)

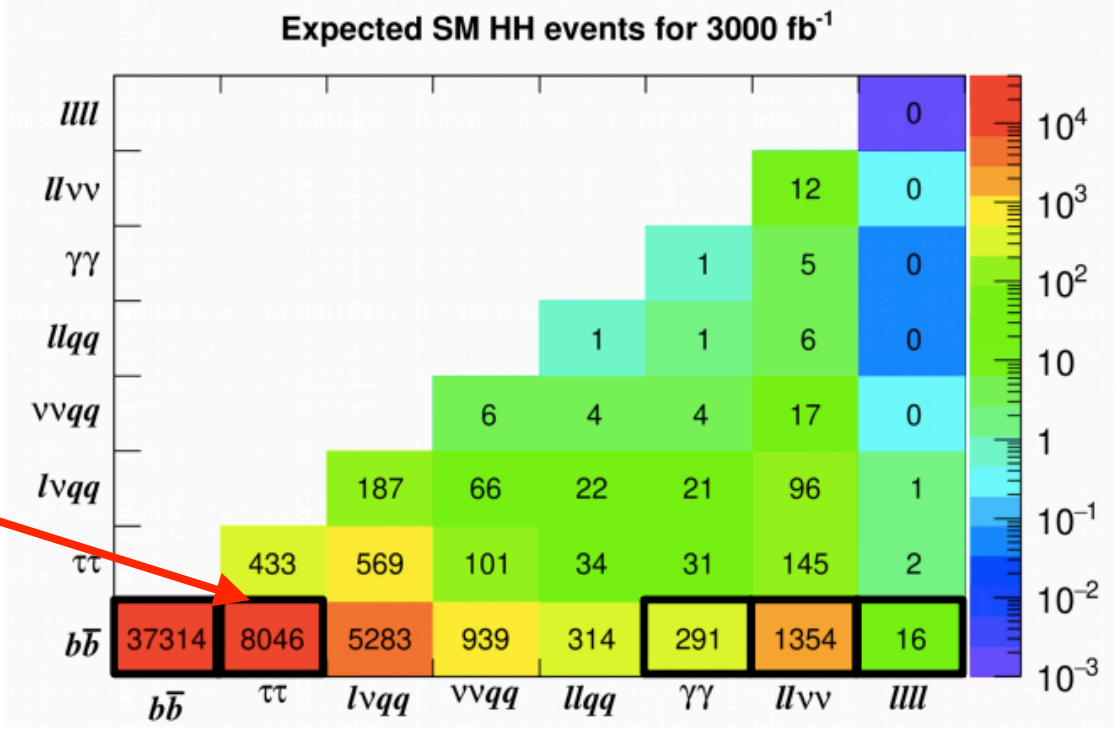




- Improving (worsening) **background modeling** helps (hurts) significantly
- Raising **jet p_T thresholds** due to trigger reduces sensitivity quite a bit

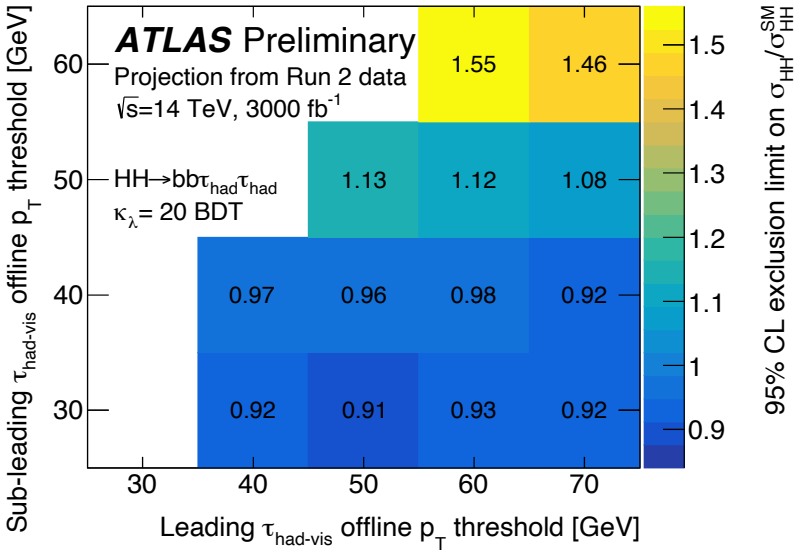
Studying HL-LHC prospects

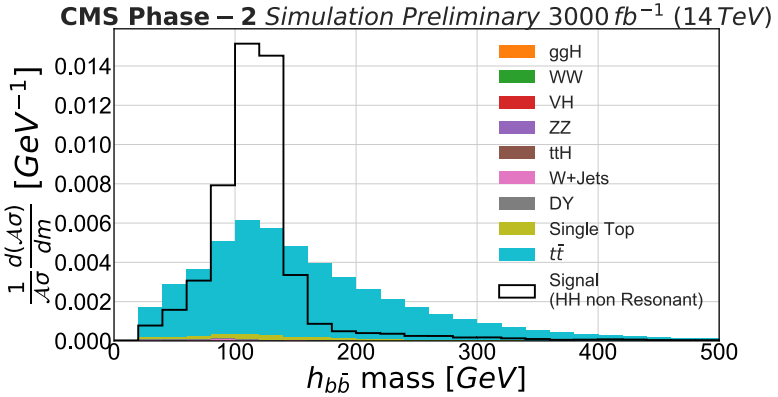
bb$\tau\tau$ channel has relatively large BR and is best current ATLAS channel. Split analysis based on tau decays (had vs lep)



ATLAS hh(bb$\tau\tau$)

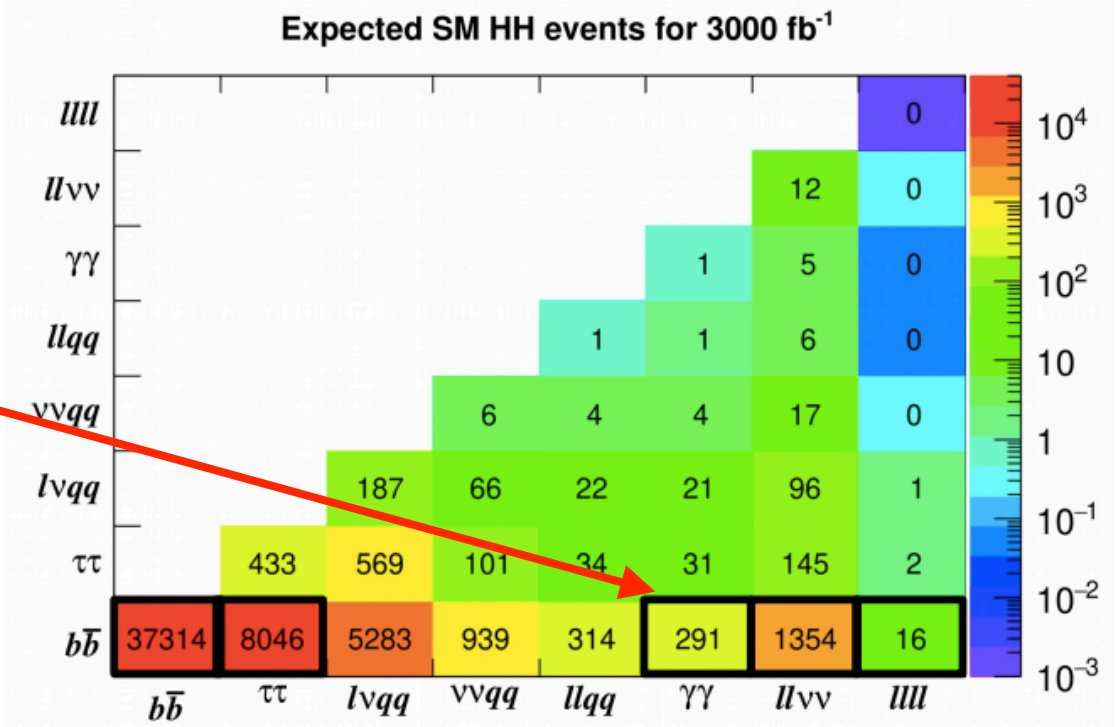
- Important question: What will **hadronic tau triggers** look like?
- Dominant backgrounds rejected with MVAs: **ttbar, QCD and Z+jets**
- Most **background normalization data-driven** and should scale with lumi
- **1.5-2.5σ evidence** at end of HL-LHC





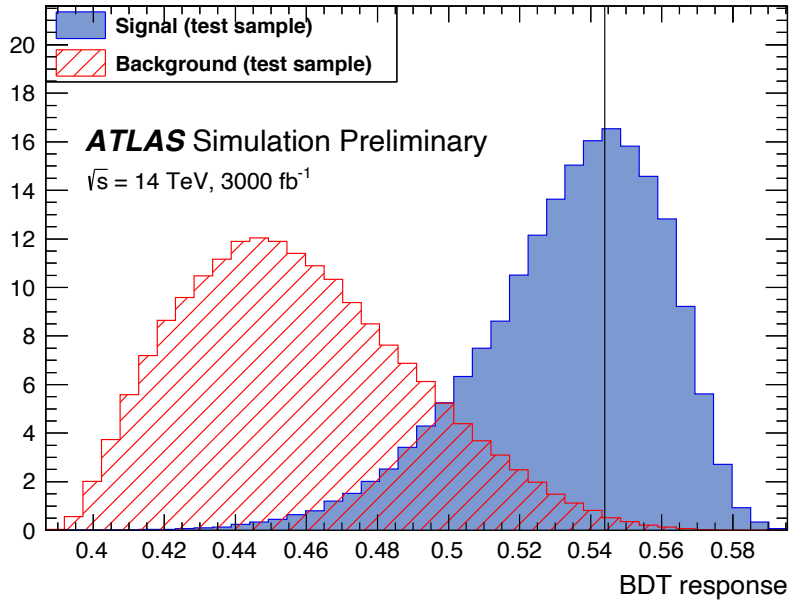
Studying HL-LHC prospects

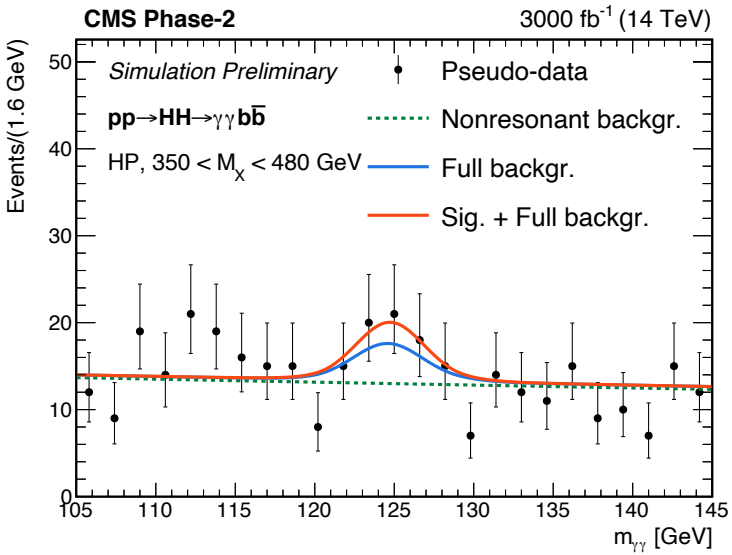
bbγγ channel has smaller BR but good mass resolution and is best current CMS channel



ATLAS hh(bbγγ)

- Take advantage of **diphoton mass resolution**
- Look for two photons and two b-jets near Higgs mass, use **MVAs to reject backgrounds** (continuum/ tth dominate)
- Split into bins of m_{HH} to improve sensitivity to multiple couplings
- **Roughly 2.0σ significance** at end of HL-LHC, systematics negligible

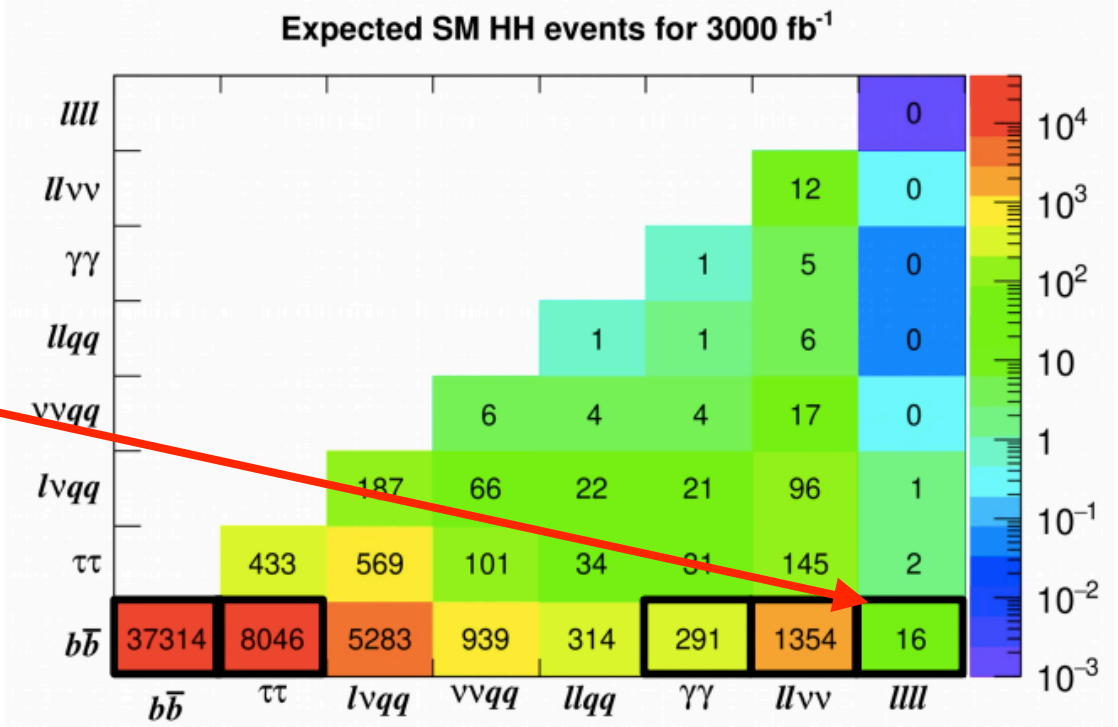




(c) $m_{\gamma\gamma}$, medium mass category

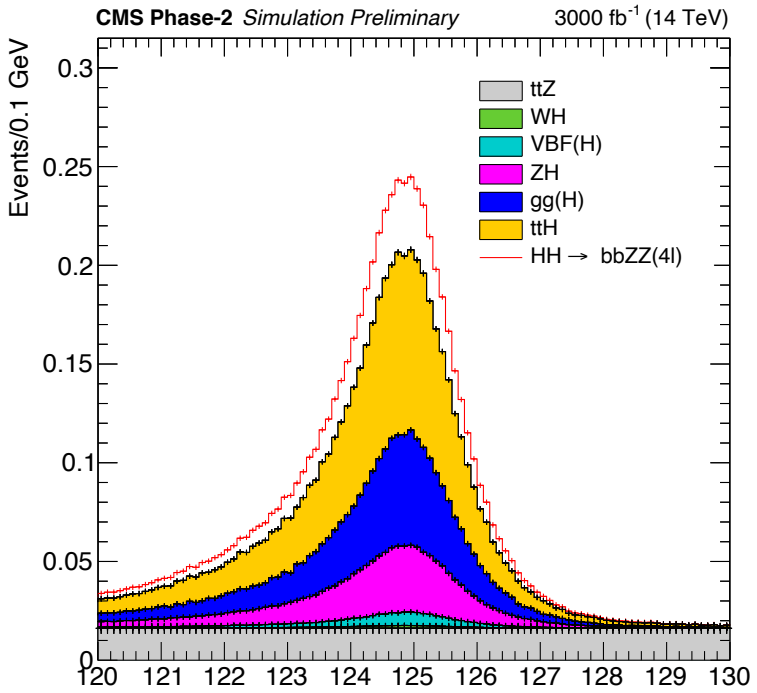
Studying HL-LHC prospects

bb+4lepton channel has very few expected events but is quite clean



CMS hh(bb+4L)

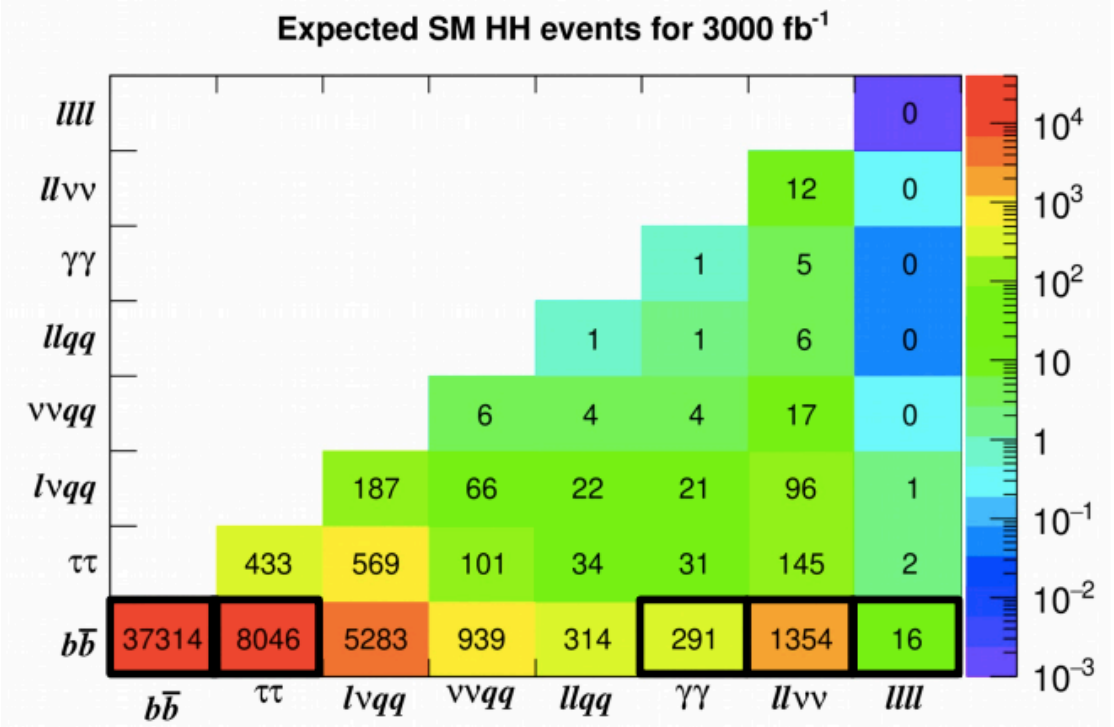
- Delphes **parametric analysis**
- **Main irreducible backgrounds**: tth(ZZ), ggH and ZH
- **Reducible ttbar and DY backgrounds** have much larger cross sections, hard to model with available Delphes samples, **assumed to be negligible**
- **Go down low in p_T** (5/7 GeV for ele/μ), form SF-OS Z candidates and make kinematic requirements



3 ab^{-1} significance 0.37σ, systematic uncertainties negligible

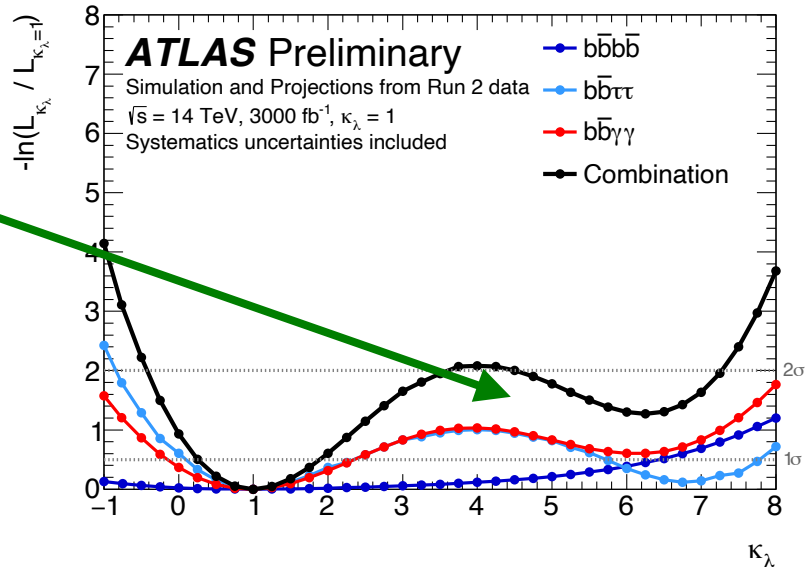
Studying HL-LHC prospects

Combinations obviously needed to study self-coupling

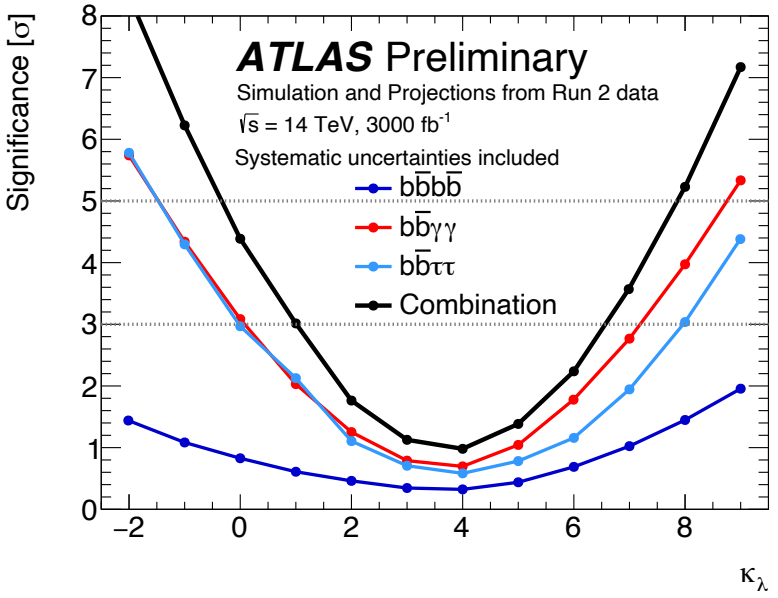


ATLAS hh combination

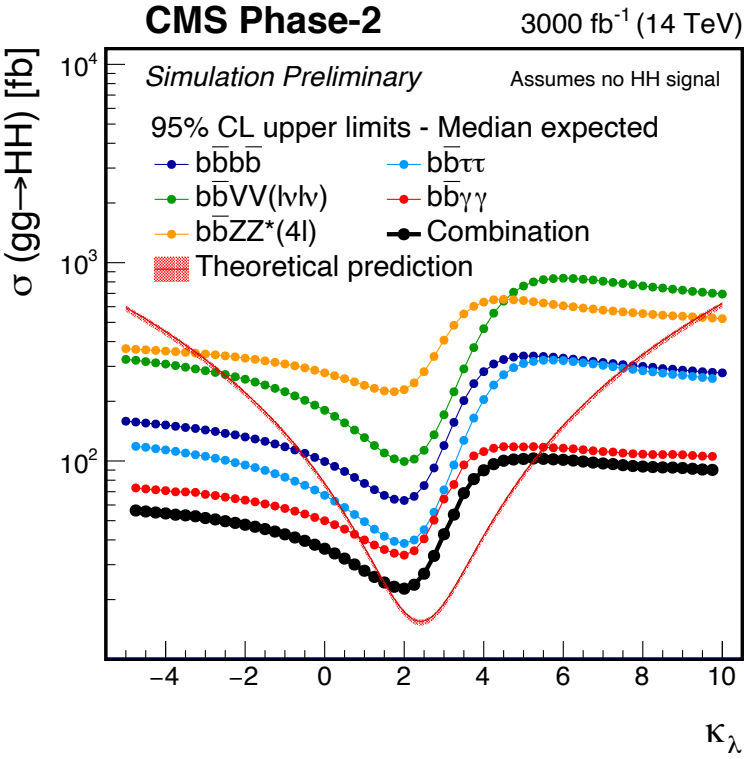
Second minimum due to signal yield similar to first minimum (m_{hh} helps break degeneracy)

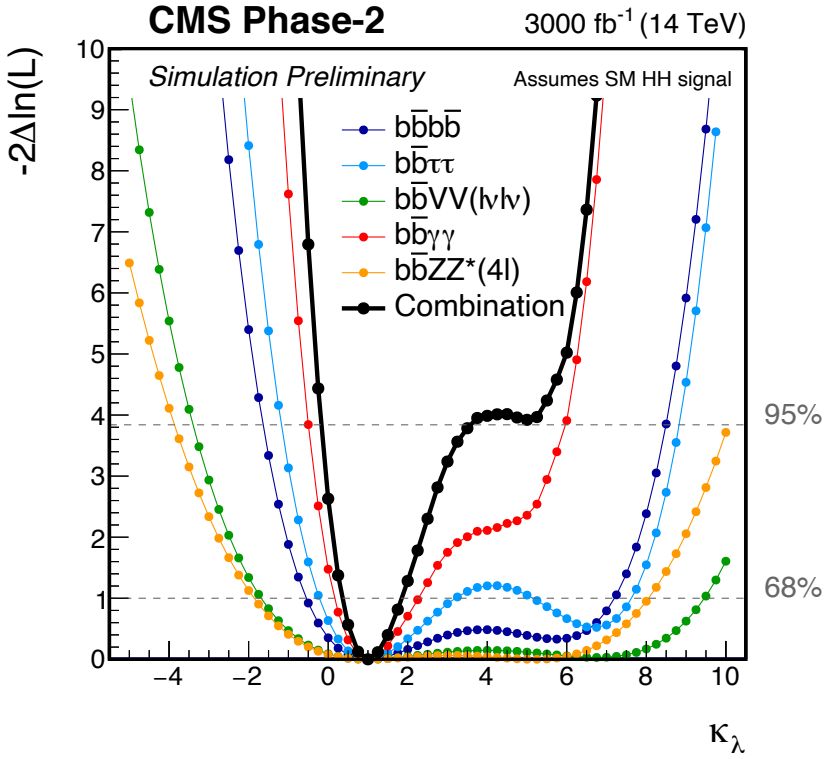


- Combine 3 dominant channels, **3.5σ evidence without (3.0σ with) systematic uncertainties**
- As expected, **sensitivity varies quite a bit if κ_λ != 1 (BSM!)**
- **Critical to combine all channels**



CMS hh combination





- Combine 5 channels, **3.6σ evidence without (2.8σ with) systematic uncertainties**
- As expected, **sensitivity varies quite a bit to BSM physics**
- **Critical to combine all channels**

HL-LHC combination

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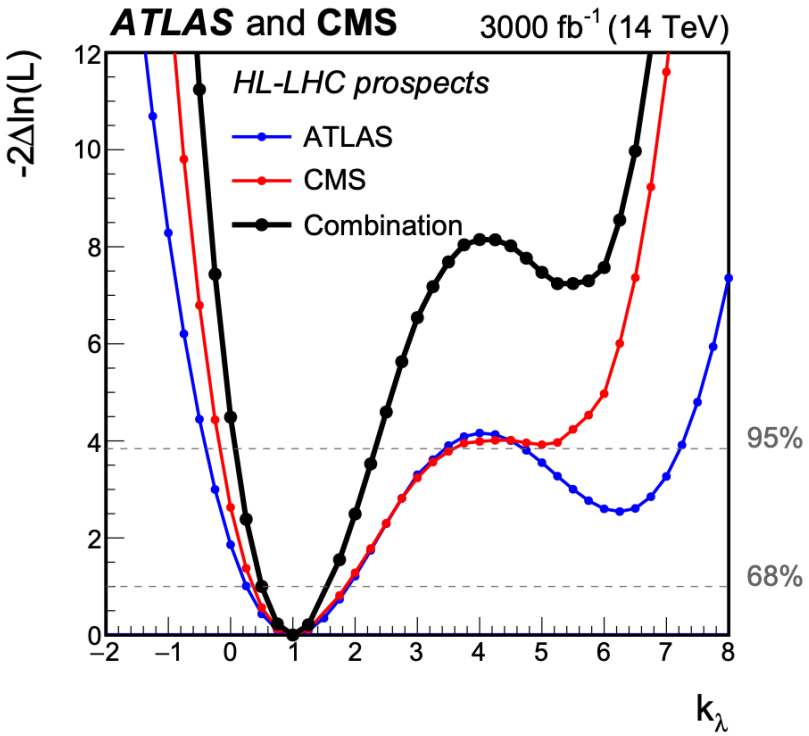
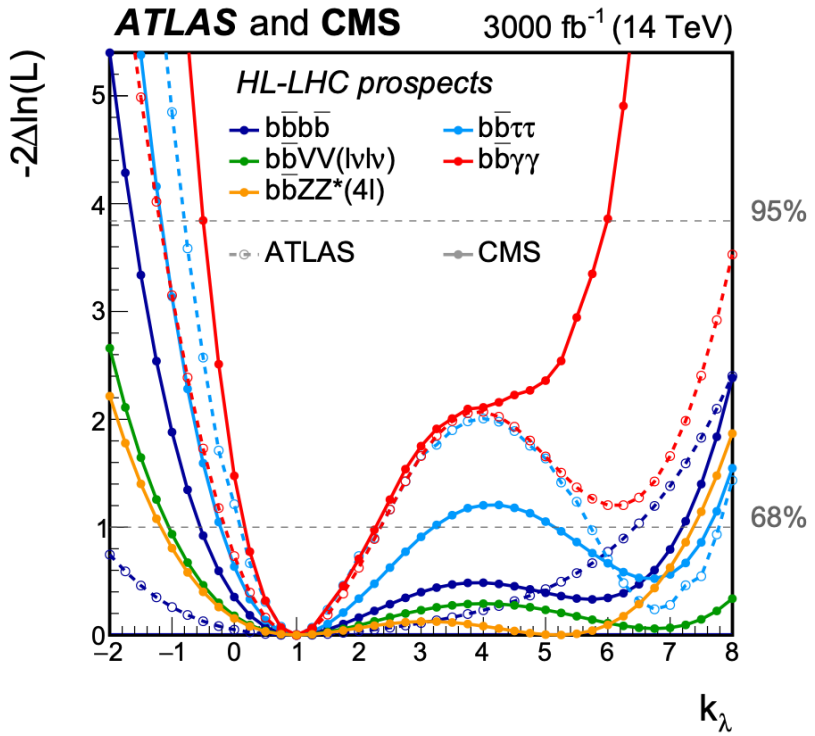




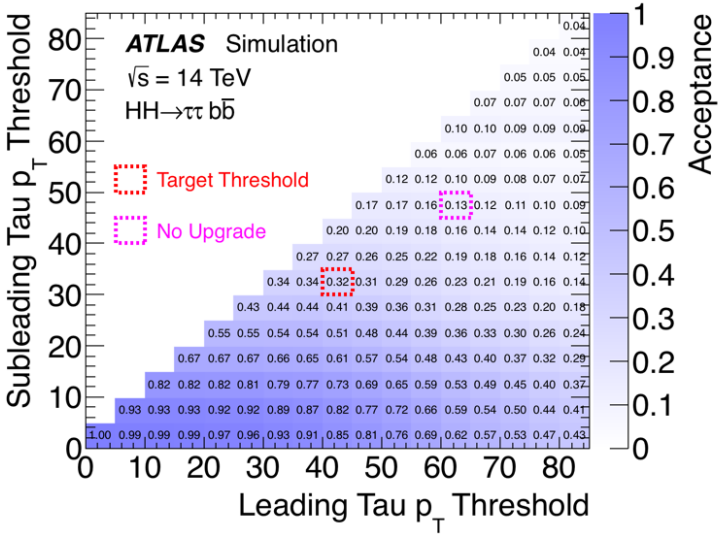
- Combine results from both experiments, **4.5σ evidence without (4.0σ with) systematic uncertainties**
- Even for the combination, **SM will be tricky to study**
- **Critical to develop new ideas, to combine with single Higgs measurements**

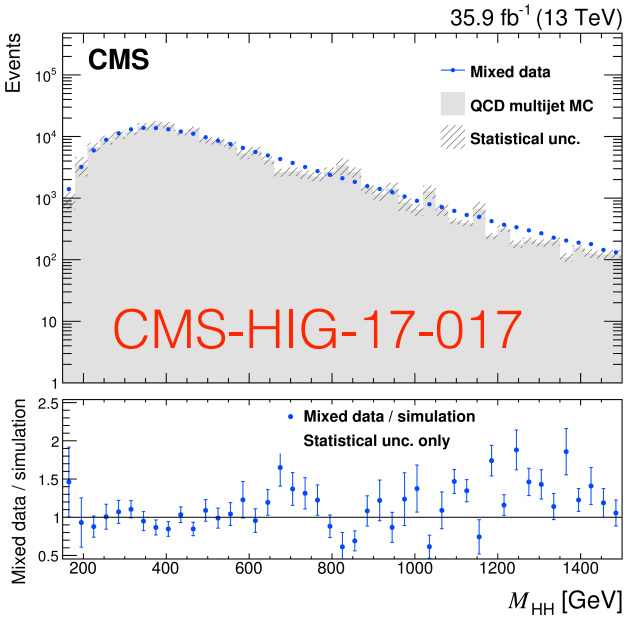
Some thoughts and ideas and lessons now that we had a taste …

Some lessons / thoughts

- **Trigger thresholds clearly critical to understand for 4b and bb$\tau\tau$.** Public results for HL-LHC upgrade: Interesting to examine? (b-jet triggers, tracks early on in trigger, asymmetric triggers, etc)
- **What about the size of the 4b multijet background?** Can more recent results be illuminating for some of the HL-LHC and/or FCC-hh studies?

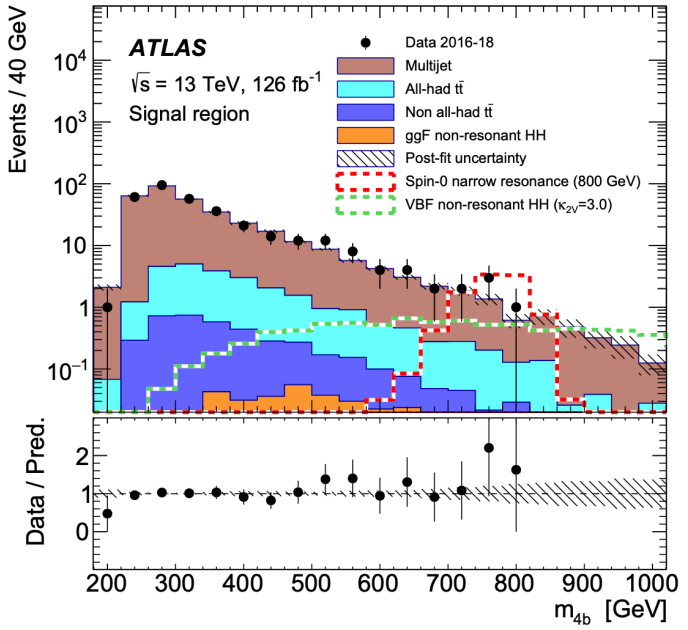
CERN-LHCC-2017-020





Some lessons / thoughts 2001.05178

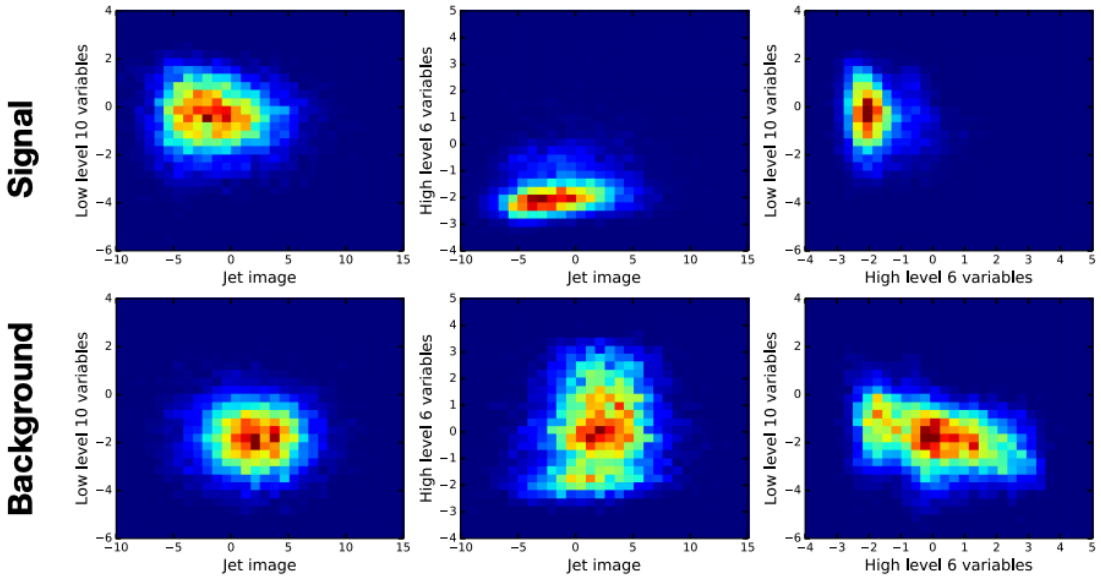
- **What about the addition of extra channels?** VBF hh (4b) helps to study extra couplings (what range of c2v are we sensitive to)? Can it improve sensitivity to overall hh? True not only for 4b analysis but perhaps also for other analyses?
- Can **VBF channel** be useful in certain BSM physics models?
- Do we have sensitivity to **VHH** at HL-LHC (or beyond) in, for example, 4b channel? And in BSM models?

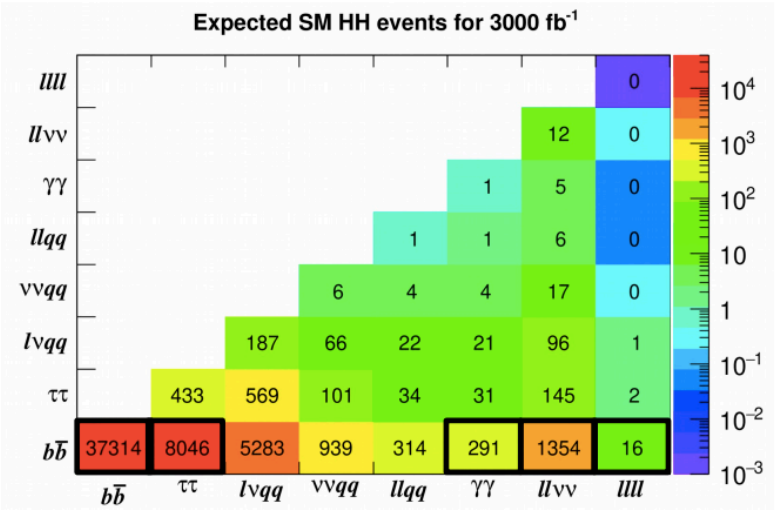


Some lessons / thoughts

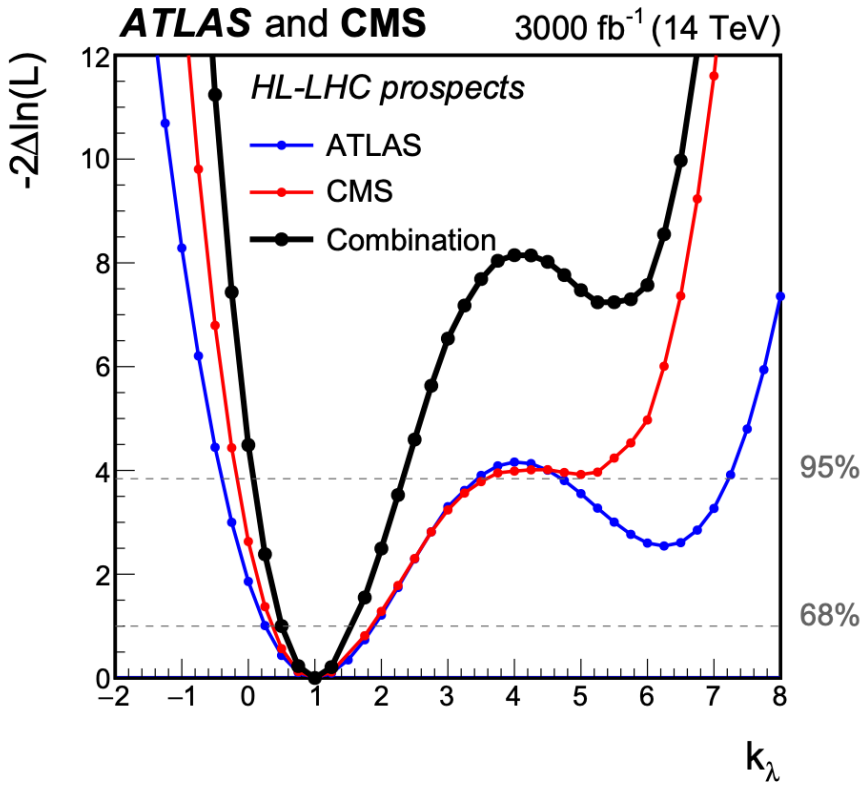
1904.08549

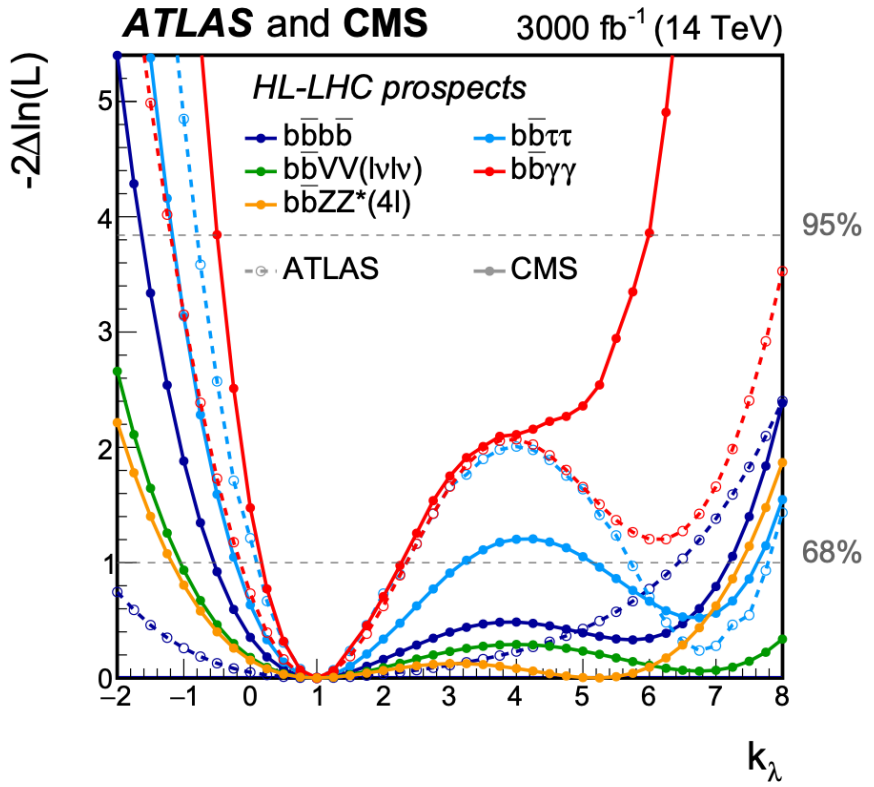
- Do we gain anything from **re-optimizing analyses using the latest MVA tools** and techniques? Maybe for new channels, but also for boosted topologies?
- Can we gain from **adding many small channels together** such as 4L + bb?





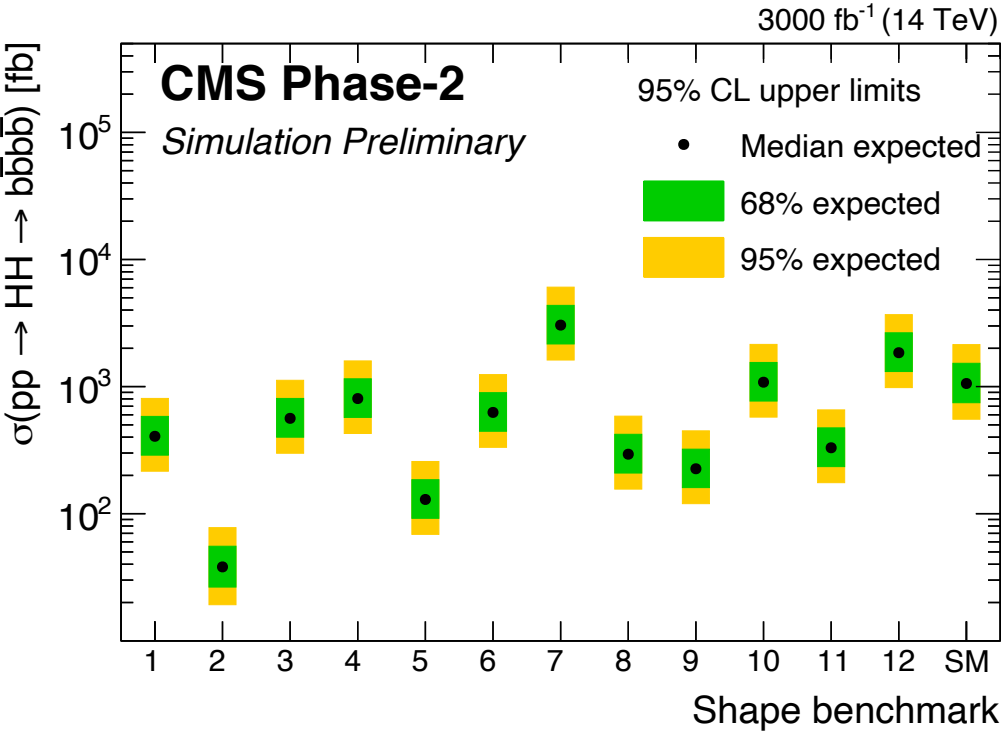
Some lessons / thoughts





Difference between 4.5σ evidence without and (4.0σ with) **systematic uncertainties** is critical. Are we missing important systematics? Perhaps to be studied? (This is tricky, of course)

Some lessons / thoughts



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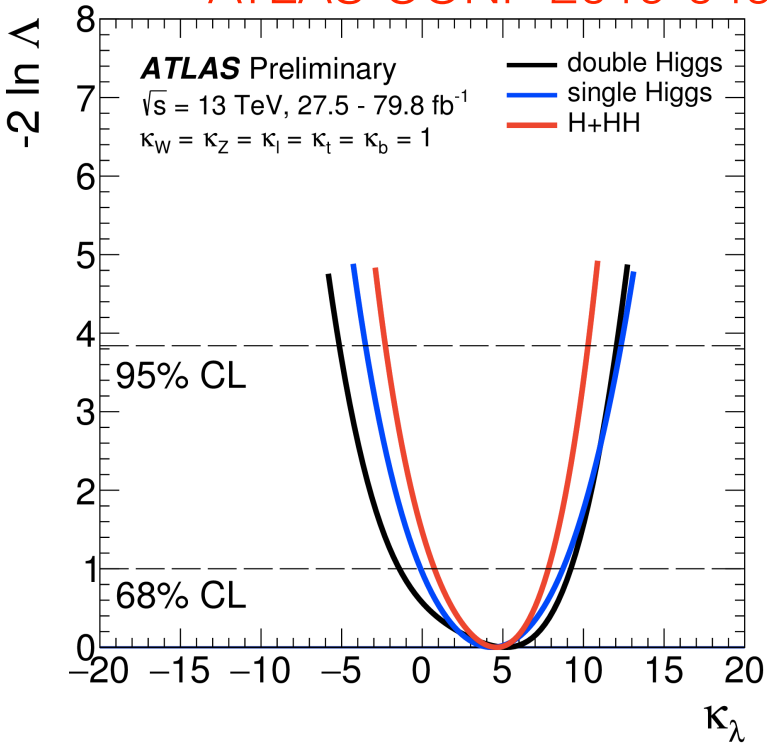


Useful to think about **EFT models and benchmark BSM** scenarios, not just for individual analyses, but also as a combination. How best to do this? Requires **shape analyses** for best sensitivity, likely a **global fit** of all channels at once. **Single Higgs** inclusion crucial, too

Some lessons / thoughts

Example from Christoph's talk at joint EF01/EF02 meeting. My takeaway from that talk: Lots of great opportunities to explore BSM physics, but a few **benchmarks are critical** for comparisons between collider options

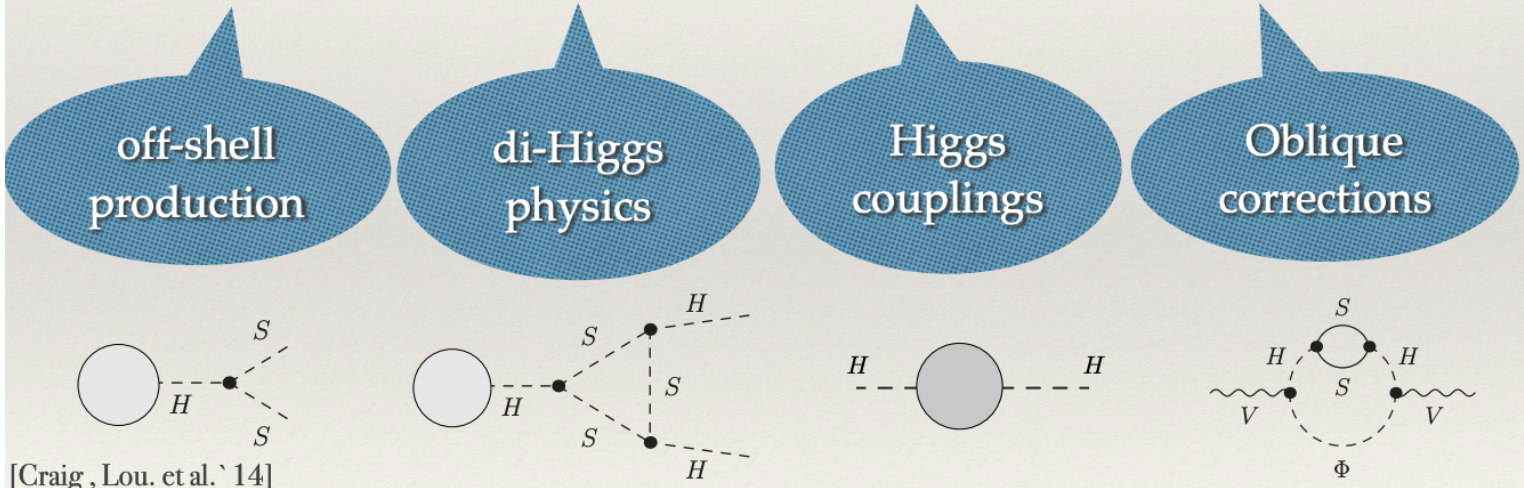
singlets above threshold

- $\mathbb{Z}_2$-symmetric Higgs portal

[Craig , Lou. et al.` 14]
[Curtin, Meade, Yu ` 14]
...

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{m_S^2}{2} S^2 - \lambda S^2 (\Phi^\dagger \Phi - v^2/2)$$

- for $m_S > m_H/2$ no direct SM Higgs decays
- BSM Higgs physics via momentum- or loop-suppressed effects



[Craig , Lou. et al.` 14]
[Ruhdorfer, Salvioni, Weiler ` 19]

[Curtin, Meade, Yu ` 14]
[He, Zhu ` 16]
[Voigt, Westhoff ` 17]

[CE, McCullough ` 13]
[Craig, CE, McCullough ` 13]
[Goncalves, Han, Mukhopadhyay ` 18]

[CE, Jaeckel, Spannowsky, Stylianou ` 20]

3

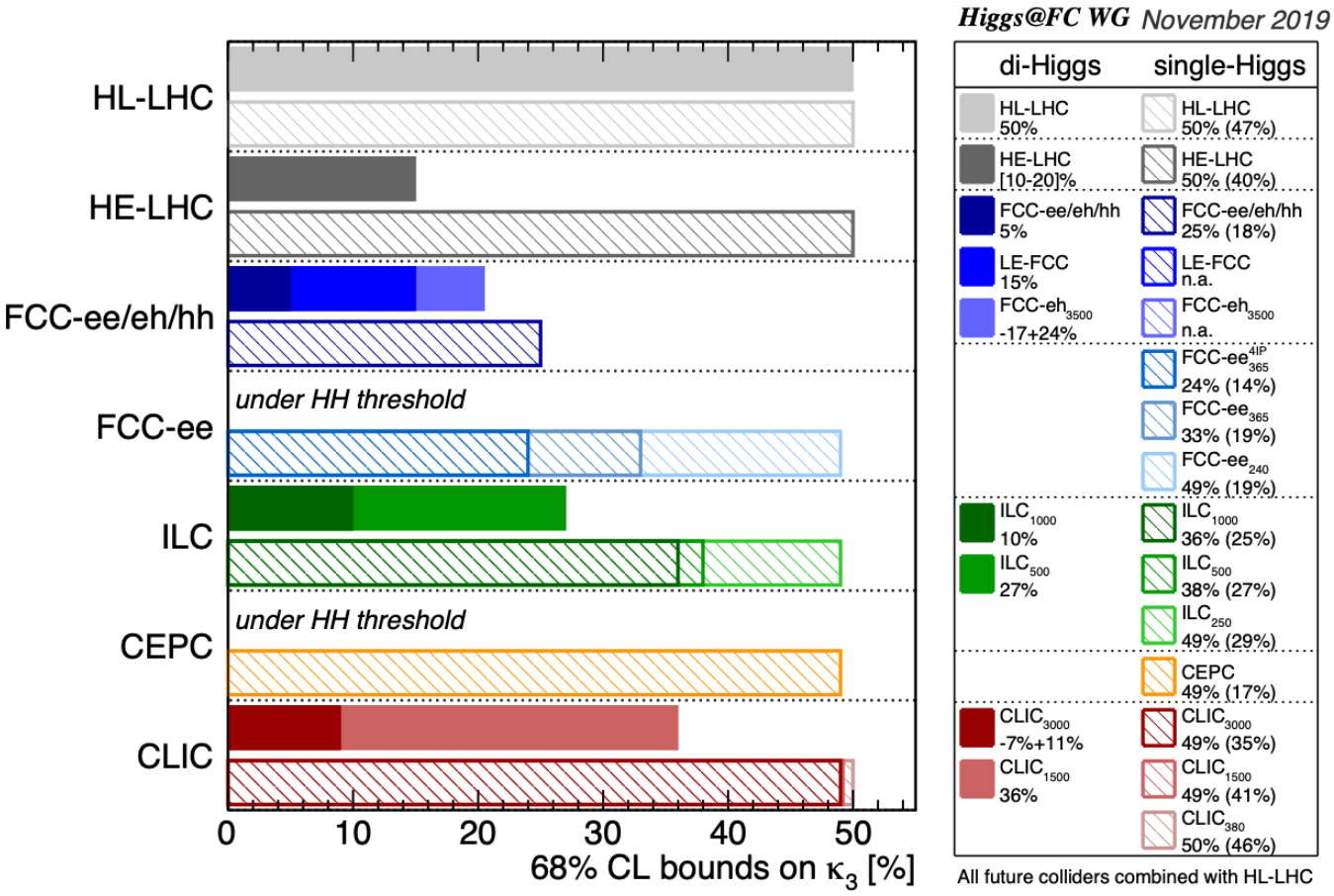
Size of ~1 sigma uncertainty on self-coupling

collider	(1) di-H excl. (hh analysis only, only allow κ_λ variations)	(2.a) di-H glob. (hh analysis only, allow single Higgs coupling variations too within uncertainties)	(3) single-H excl. (Single h analysis only, only allow EFT variations corresponding to κ_λ shifts) with HL-LHC	(3) single-H excl. w/o HL-LHC	(4) single-H glob. (Single h analysis only, allow all possible coupling variations)
HL-LHC	$^{+60}_{-50}$% (50%)	52%	47%	125%	50%
HE-LHC	10-20% (n.a.)	n.a.	40%	90%	50%
ILC_{250}	–	–	29%	126%	49%
ILC_{350}	–	–	28%	37%	46%
ILC_{500}	27% (27%)	27%	27%	32%	38%
ILC_{1000}	10% (n.a.)	10%	25%	n.a.	36%
$CLIC_{380}$	–	–	46%	120%	50%
$CLIC_{1500}$	36% (36%)	36%	41%	80%	49%
$CLIC_{3000}$	$^{+11}_{-7}$% (n.a.)	n.a.	35%	65%	49%
FCC-ee_{240}	–	–	19%	21%	49%
FCC-ee_{365}	–	–	19%	21%	33%
FCC-ee^{4IP}_{365}	–	–	14%	n.a.	24%
FCC-eh	17-24% (n.a.)	n.a.	n.a.	n.a.	n.a.
FCC-ee/eh/hh	5% (5%)	6%	18%	19%	25%
LE-FCC	15% (n.a)	n.a	n.a.	n.a.	n.a.
CEPC	–	–	17%	n.a.	49%

Clear that combinations with single Higgs measurements are critical, and also that FCC-hh will significantly improve constraints

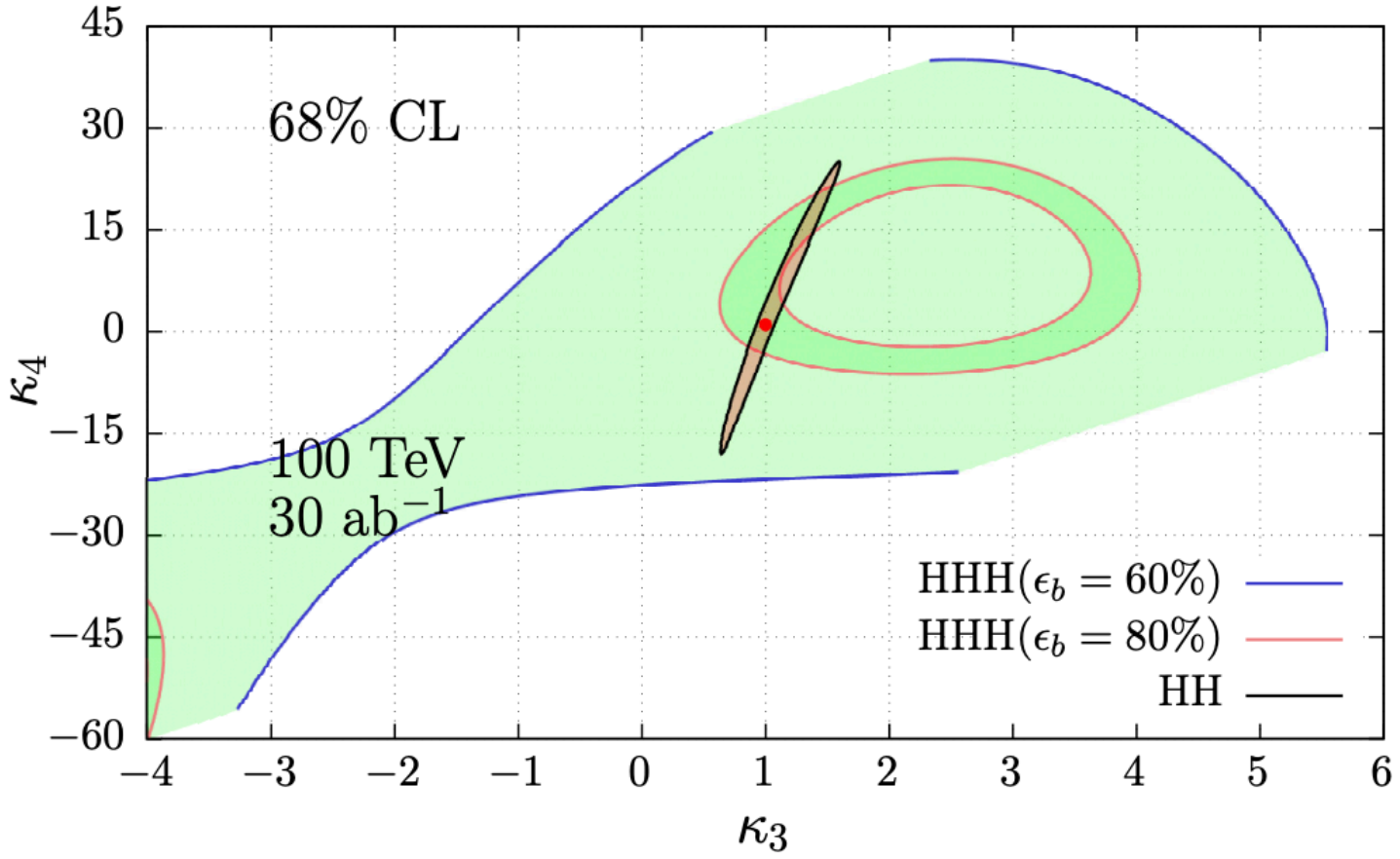
collider	(1) di-H excl.	(2.a) di-H glob.	(3) single-H excl.		(4) single-H glob.
			with HL-LHC	w/o HL-LHC	
HL-LHC	$^{+60}_{-50}$% (50%)	52%	47%	125%	50%
HE-LHC	10-20% (n.a.)	n.a.	40%	90%	50%
ILC_{250}	–	–	29%	126%	49%
ILC_{350}	–	–	28%	37%	46%
ILC_{500}	27% (27%)	27%	27%	32%	38%
ILC_{1000}	10% (n.a.)	10%	25%	n.a.	36%
$CLIC_{380}$	–	–	46%	120%	50%
$CLIC_{1500}$	36% (36%)	36%	41%	80%	49%
$CLIC_{3000}$	$^{+11}_{-7}$% (n.a.)	n.a.	35%	65%	49%
FCC-ee_{240}	–	–	19%	21%	49%
FCC-ee_{365}	–	–	19%	21%	33%
FCC-ee^{4IP}_{365}	–	–	14%	n.a.	24%
FCC-eh	17-24% (n.a.)	n.a.	n.a.	n.a.	n.a.
FCC-ee/eh/hh	5% (5%)	6%	18%	19%	25%
LE-FCC	15% (n.a)	n.a	n.a.	n.a.	n.a.
CEPC	–	–	17%	n.a.	49%

Another view



Challenge for FCC-hh: 1% uncertainty on **top quark Yukawa coupling** leads to 5% uncertainty on Higgs self-coupling!

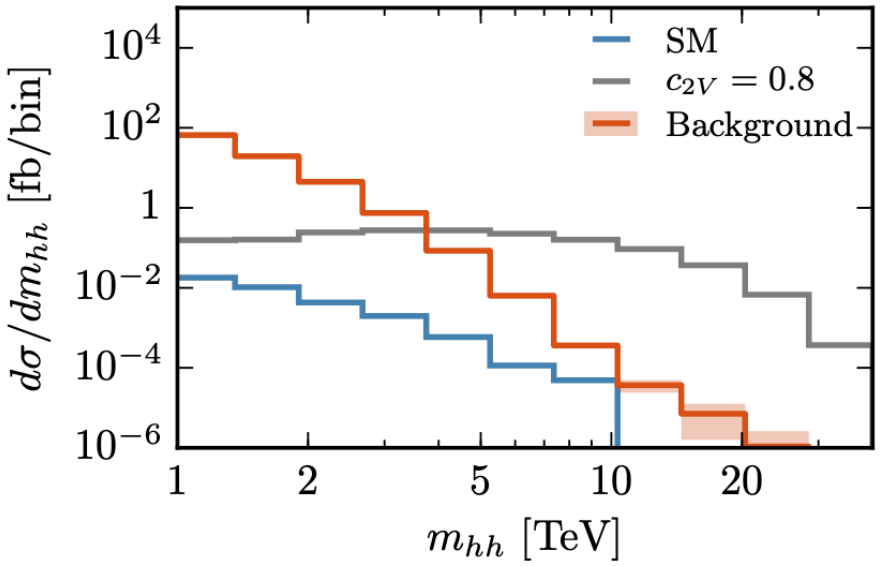
Quartic couplings?

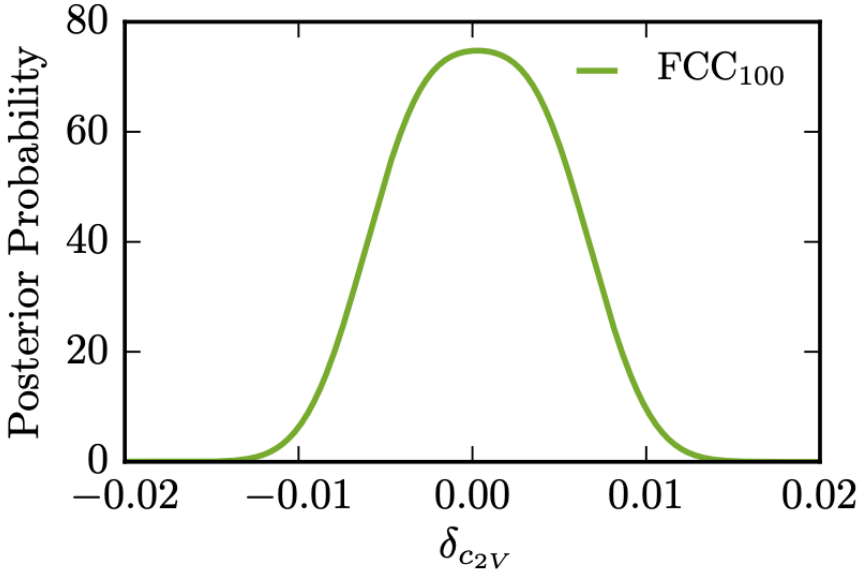


Quartic Higgs coupling also very interesting to study, but cross sections even smaller. Perhaps FCC-hh has an ability to set limits on this?

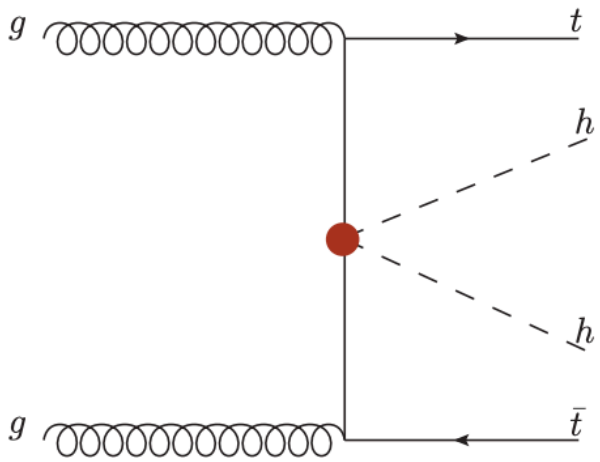
Other couplings at FCC-hh

hh White paper





FCC-hh provides an opportunity to better study the **hhVV** coupling (not yet in the context of VBF for more general hh searches) and also **tthh** coupling



$$-0.24\,\text{TeV}^{-1} < \kappa_{t\bar{t}hh} < 0.60\,\text{TeV}^{-1} \quad 30/\text{ab}.$$

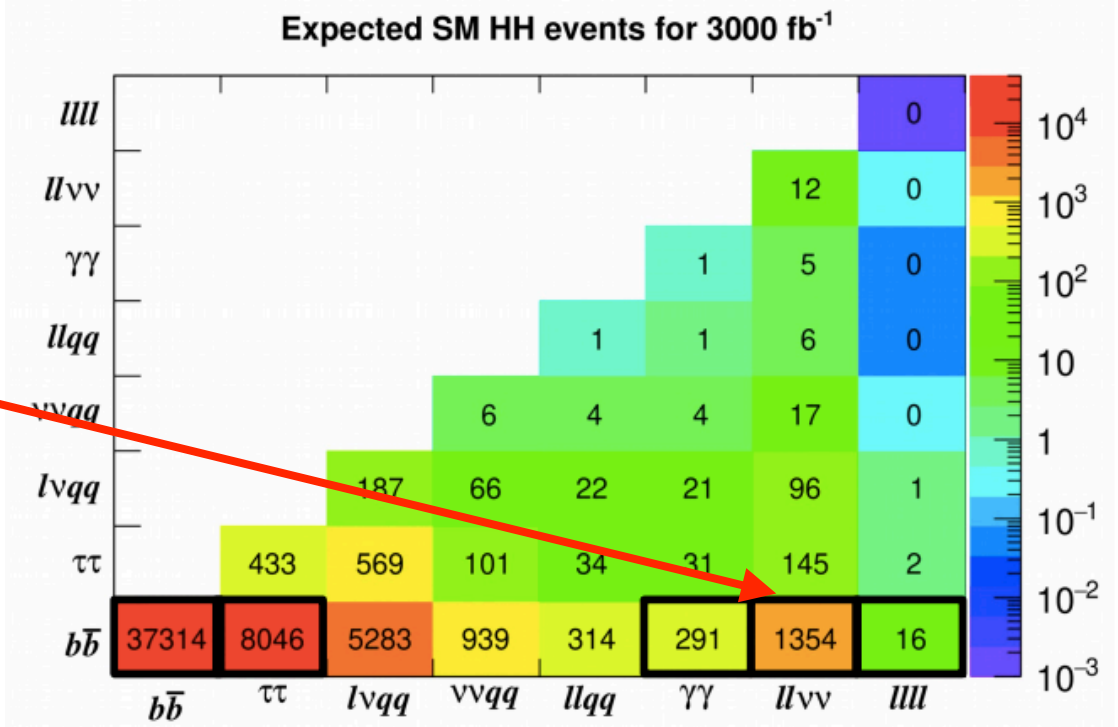
Recap of non-exhaustive list of things to think about

- **4b/bb$\tau\tau$:** Rethinking triggers?
- **4b/bb$\tau\tau$: Systematic uncertainties?**
- **4b:** Any updates on size of multi-jet backgrounds?
- **4b:** Quartic coupling sensitivity?
- **All:** VBF? For BSM? Improving sensitivity? c2V?
- **All:** Vhh? tthh?
- **All:** Latest MVA tools? For boosted? Otherwise?
- **New channel:** Adding small, missing channels?
- **All:** Benchmarks for BSM? Models and parameters
- **Combination:** Updates on single Higgs inclusion?


Higgs boson
Higgs boson

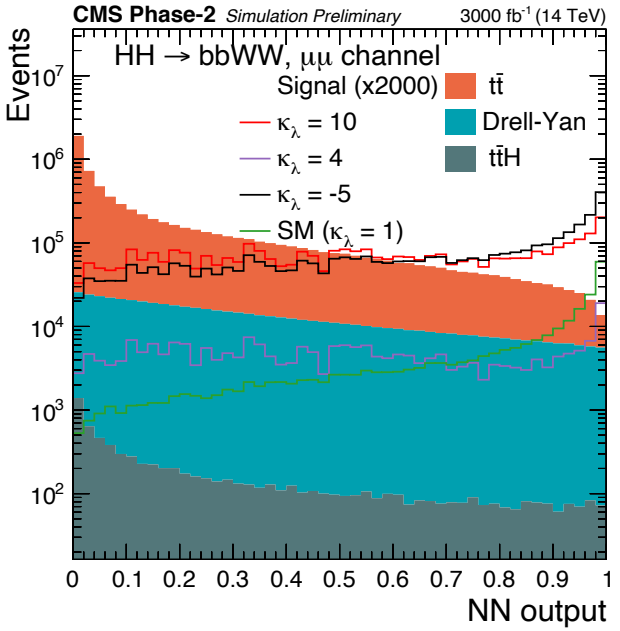
Studying HL-LHC prospects

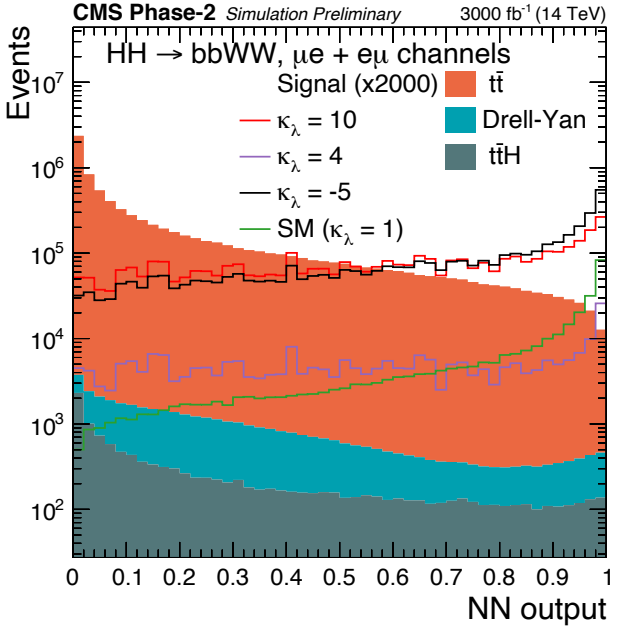
bbll$\nu\nu$ channel dominated by bbWW decays, but also includes bbZZ



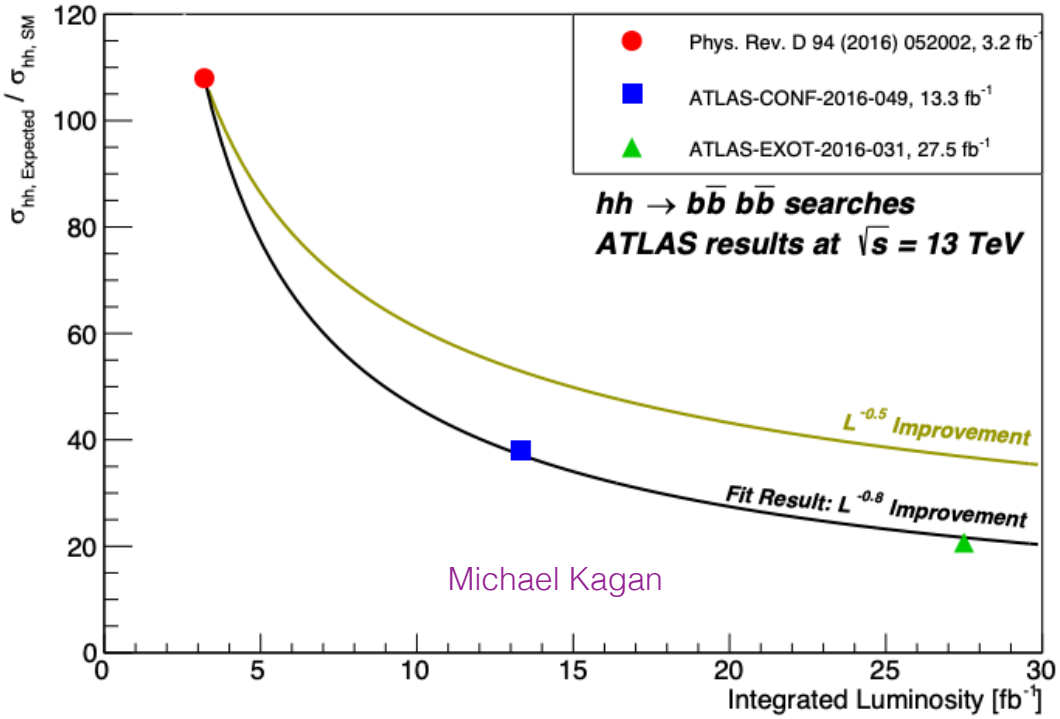
CMS hh(bbll)

- Delphes **parametric analysis**
- Background dominated by **ttbar and Z+jets** (dilepton mass cuts to reject Z+jets and quarkonium decays)
- Use a **NN with kinematic quantities as input** to separate signal and background
- **95% CL upper limit** of 3.5 x SM cross section (3.3 without systematics)

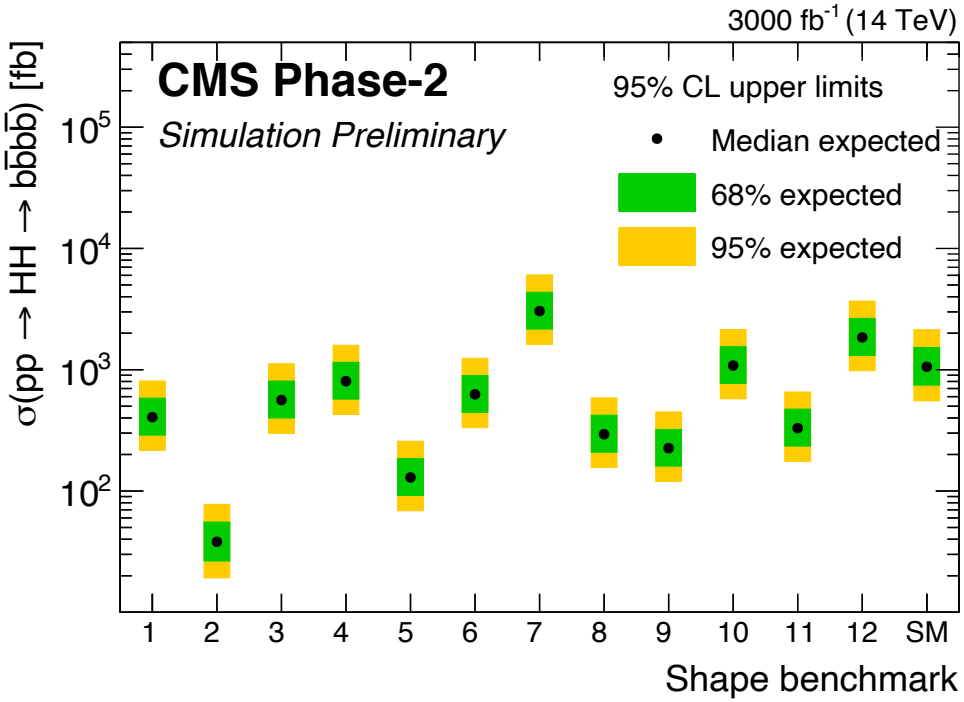




Scaling with luminosity?



We are getting smarter and more clever, and results scale better than naive expectation. Bodes well for the future?



Significant differences in expected upper limits depending on the benchmark model chosen